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# Assessment of Preconditioner for a USM3D Hierarchical Adaptive Nonlinear Iteration Method (HANIM) (Invited)

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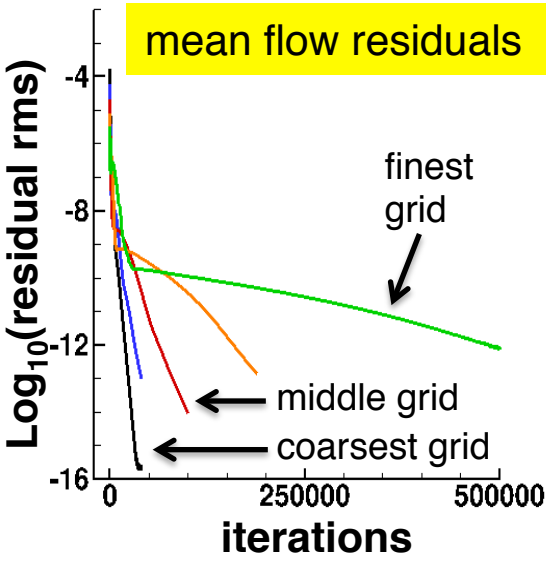
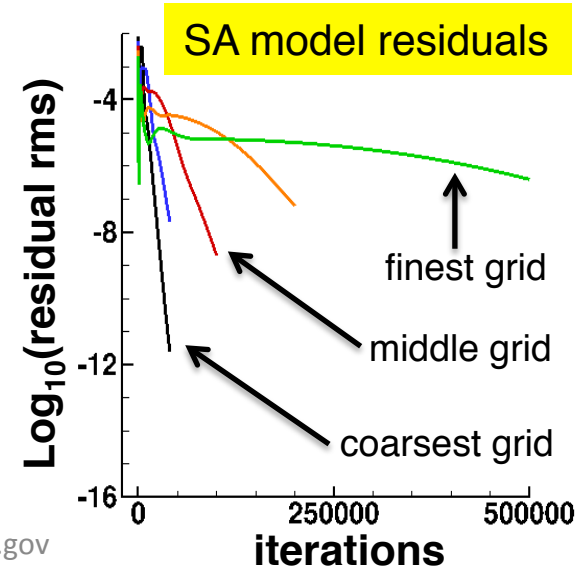
# Outline

- Background and Motivation
- Summary of Present Extensions
- Overview of USM3D Solution Methods
- Results
- Concluding Remarks
- Future Directions

# Background and Motivation

- **Initial mixed-element USM3D version in 2012 (AIAA-2013-2541)**
  - extends USM3D tetrahedral grid CFD code to support various cell topologies
  - "preconditioner-alone" (PA) baseline solver technology to advance nonlinear solution in pseudo-time
  - preconditioner based on defect-correction scheme and point-implicit Gauss-Seidel solution method
- **Sluggish iterative convergence on finer grids**
  - 2D bump-in-channel finest grid solution after 500,000 nonlinear iterations
    - forces and moment almost converged, residuals several orders above machine-zero

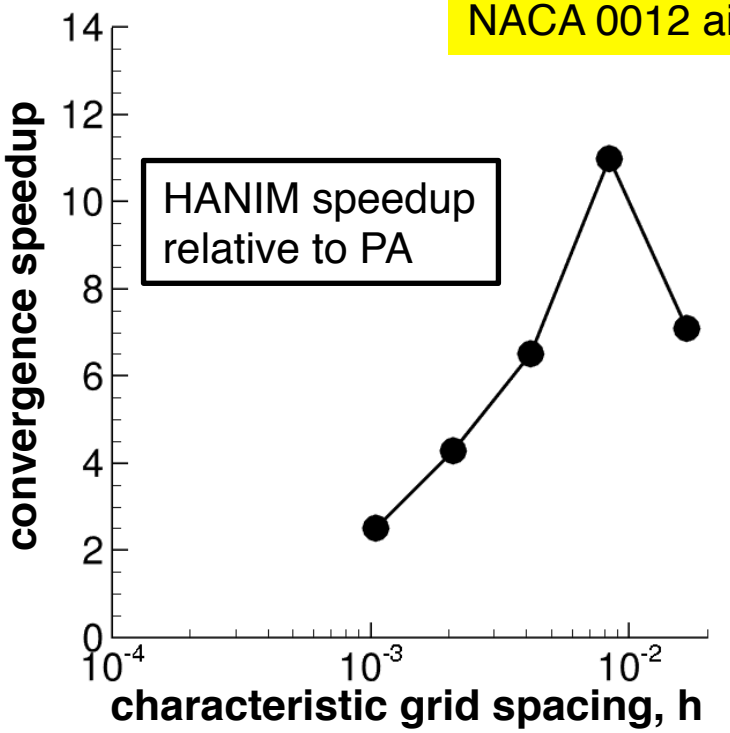


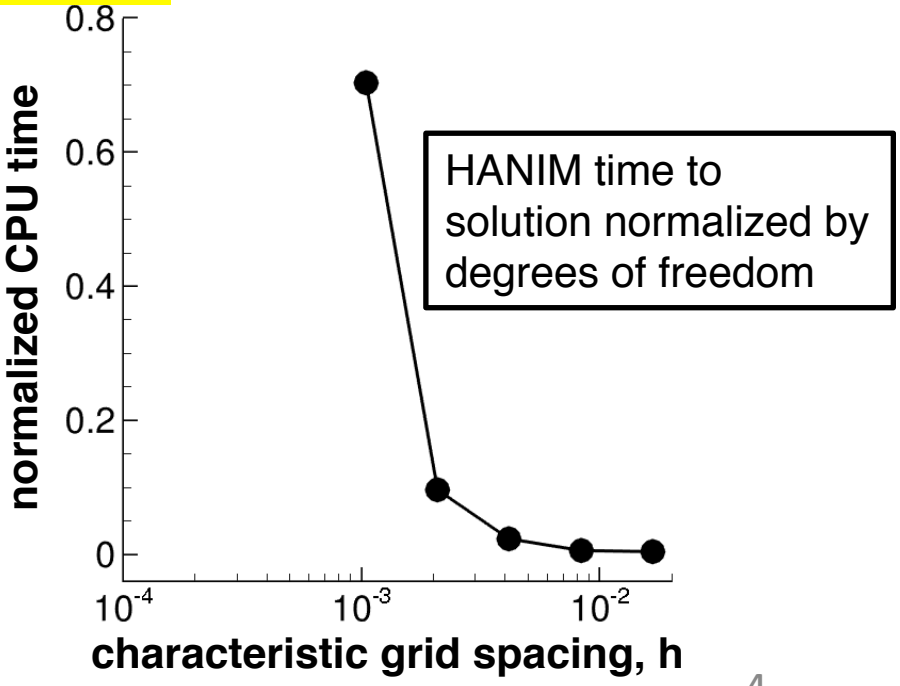



# Background and Motivation

- **USM3D mixed-element version enhanced in 2014 for improved iterative convergence and robustness (AIAA-2015-1747)**
  - Hierarchical Adaptive Nonlinear Iteration Method (HANIM)
    - similar to other recent approaches at NASA (FUN3D), Boeing (GGNS), etc.
  - convergence speedup factor of 1.4 to 13 relative to the baseline PA method
- **Diminished convergence acceleration on finer grids**

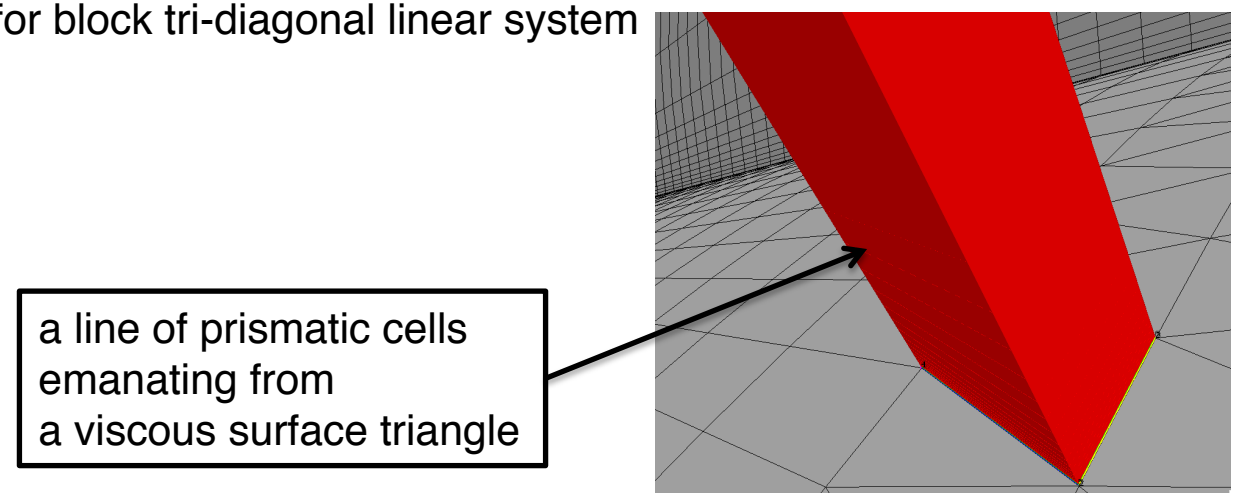
NACA 0012 airfoil solutions



# Summary of Present Extensions

- **Multicolor line-implicit preconditioner**
  - highly-anisotropic grids typically used for turbulent flow computations
  - line-implicit preconditioner can efficiently reduce high-frequency errors in the directions of small and large mesh spacing
  - point-implicit preconditioner can be inefficient on highly-anisotropic grids
  - line generation algorithm implemented
    - extracts a sequence of ordered cells that share a face
    - relies only on grid connectivity, does not use geometric/discretization information
    - currently limited to prismatic and hexahedral grids
  - Thomas algorithm for block tri-diagonal linear system



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# Summary of Present Extensions

- **Improved discretization of turbulence model source terms**
  - velocity gradients modified using a line-mapping method
    - relies on line structure
- **Discretely-consistent and general symmetry boundary condition**
  - intersection of up to 3 symmetry boundary patches, angle between two symmetry boundary patches can be any divisor of 360°
  - new procedures for computing nodal averaging, fluxes, and flux linearization
    - gradient, nodal averaging, and flux reconstruction stencils not biased
- **Grid sequencing for solution initialization**
  - currently limited to structured grids
- **Preconditioner optimization**
  - static residuals to monitor convergence of preconditioner
  - residual reduction target changed from 0.1 to 0.5
    - improved efficiency observed for HANIM solutions using point-implicit preconditioner (up to factor 2.3)


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# Overview of USM3D Nonlinear Solution Methods

- **System of nonlinear equations, $R(Q) = 0$**
- **Two different methods for nonlinear iterations**
  - Preconditioner-Alone (PA) method
  - Hierarchical Adaptive Nonlinear Iteration Method (HANIM)
- **PA method**
  - baseline code technology with improved discretization and preconditioner
- **HANIM**
  - significant improvements over PA in robustness and iterative convergence
  - enhanced solver for the system of nonlinear equations
  - provides two additional hierarchies around the preconditioner of PA
    - matrix-free linear solver for the exact linearization of nonlinear RANS equations
    - nonlinear control of solution updates
  - CFL adaptation used as a comprehensive tool


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# PA Method

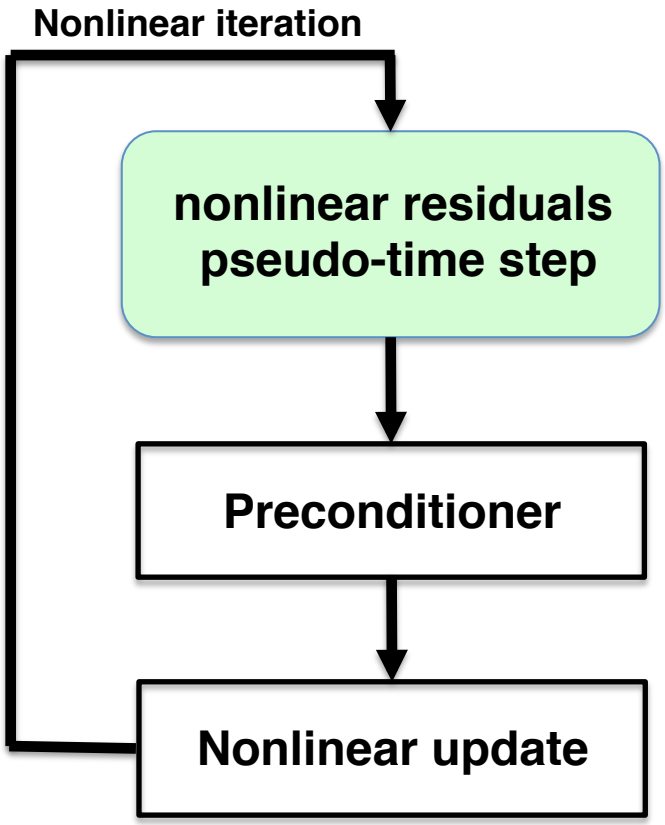
- **Baseline code technology with improved discretization and preconditioner**
  - first-order FDS scheme for mean flow approximate Jacobian
  - point- or line-implicit scheme for solving preconditoner equations
  - residual reduction targets for preconditioner

$$\frac{V}{\Delta\tau}\Delta Q + \frac{\partial \hat{R}}{\partial Q}\Delta Q = -R\left(Q^n\right)$$

← Solved by Preconditioner

$$Q^{n+1} = Q^n + \Delta Q$$

← Performed inside Nonlinear Update




**PA Flowchart**



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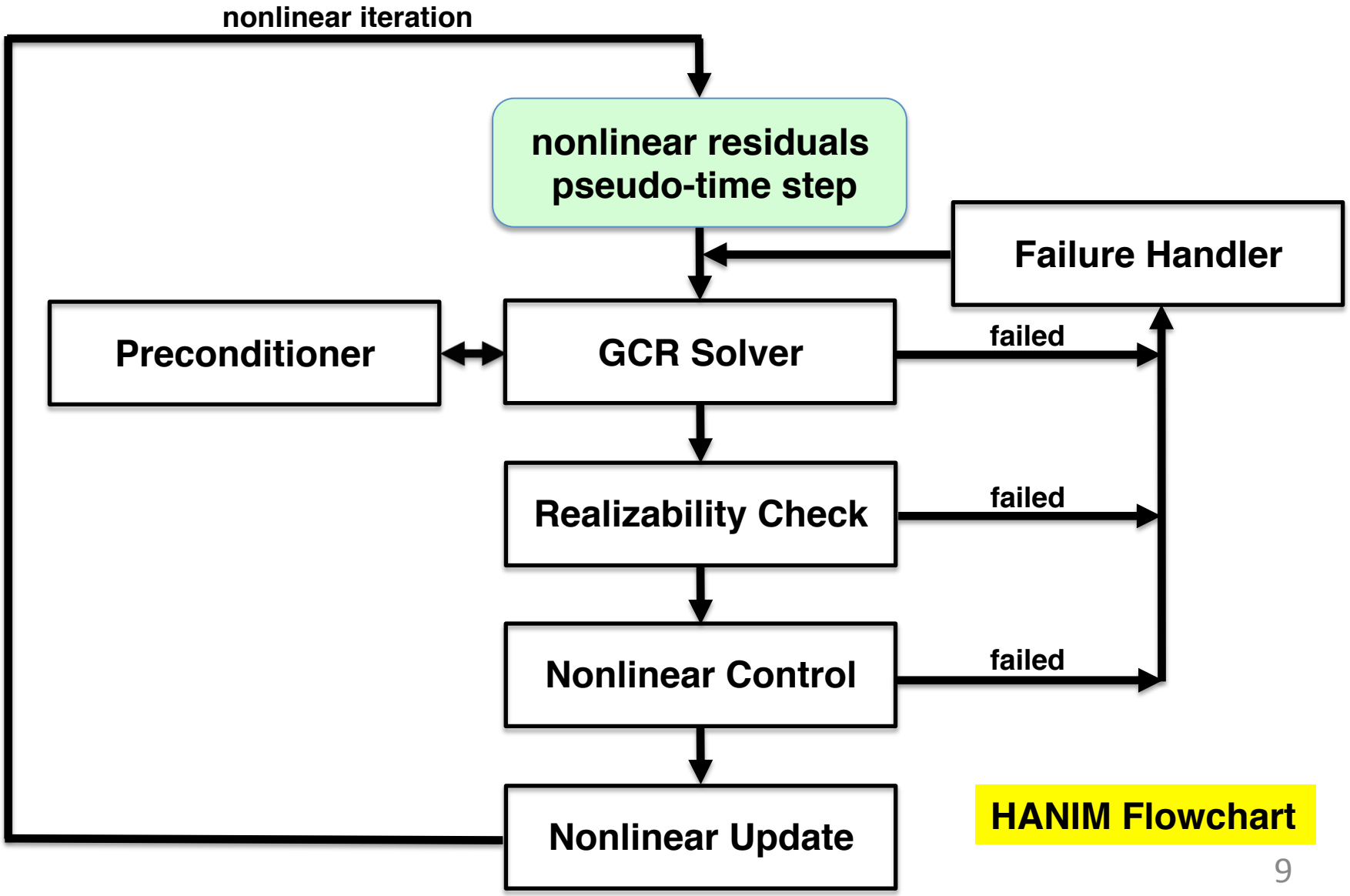
# Hierarchical Adaptive Nonlinear Iteration Method(HANIM)




**HANIM Flowchart**



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# HANIM Modules
## Preconditioner, GCR Solver, Realizability Check, Nonlinear Control

- **Preconditioner generates a new search direction for GCR**
- **GCR Solver uses Generalized Conjugate Residual (GCR) method**
  - matrix-free linear solver for $\frac{V}{\Delta\tau}\Delta Q + \frac{\partial R}{\partial Q}\Delta Q = -R\left(Q^n\right)$
  - Frechet derivative used for $\frac{\partial R}{\partial Q}\Delta Q$ — exact Jacobian
  - suggests updates, $\Delta Q$, for current nonlinear solution
- **Realizability Check module checks for non-physical solution state using updates, $\Delta Q$, from GCR Solver module**
- **Nonlinear Control reduces nonlinear residuals to a specified target $Q = Q^n + \omega\Delta Q$**
  - finds optimal under-relaxation parameter, $\omega$, for updates from GCR-Solver
  - quadratic search used for under-relaxation parameter

# Results

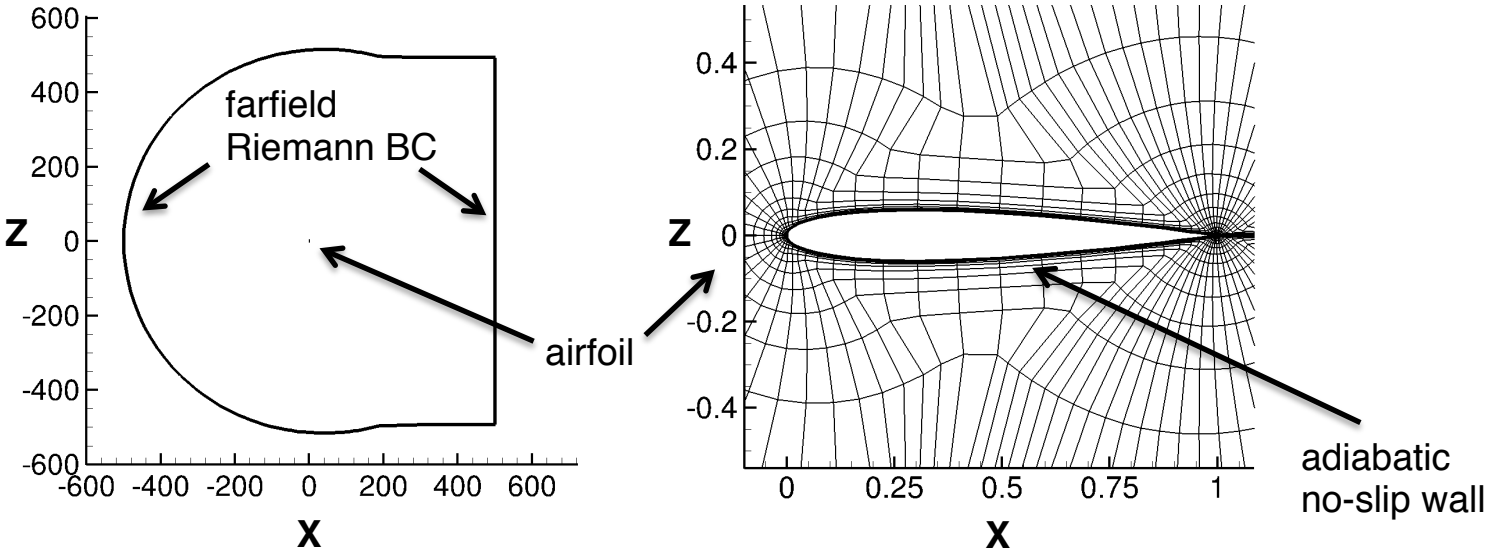
- **Steady-state Reynolds-averaged Navier-Stokes (RANS) solutions**
  - 2D bump-in-channel
  - 2D NACA 0012 airfoil
  - 3D bump-in-channel
  - 3D hemisphere-cylinder
- **Grids from NASA Turbulence Modeling Resource (TMR) website**
  - uniformly-refined nested grids
- **3 different solution sets**
  - HANIM solutions using line-implicit preconditioner (LI-HANIM)
  - HANIM solutions using point-implicit preconditioner (PI-HANIM)
  - PA method solutions using point-implicit preconditioner (PA)
- **Convergence of LI-HANIM assessed relative to PI-HANIM and PA**
- **Solution convergence criteria**
  - rms norm of combined mean flow and turbulence model residuals $\leq 10^{-13}$
  - aerodynamic coefficients converged to six significant digits

# Key Solution Parameters

- **Spalart-Allmaras (SA) model; *negative* variant**
- **Mean flow convective terms: second-order, Roe's FDS**
- **SA model convective term: first-order**
- **Mean flow approximate Jacobian convective terms: first-order, FDS**
- **Preconditioner: maximum 500 G-S iterations, residual reduction target 0.5**
- **HANIM parameters**
  - only 1 search direction for GCR Solver
  - linear residual reduction target for GCR Solver module: 0.96
  - nonlinear residual target for Nonlinear Control module: 0.92
  - adaptive CFL, 1 for the first nonlinear iteration
    - If all modules declare success increase CFL by factor 2
    - If any module declares failure, reduce CFL by factor 10
  - two different solutions using point-implicit preconditioner (PI-HANIM) and line-implicit preconditioner (LI-HANIM)
- **PA parameters:**
  - point-implicit preconditioner
  - prescribed CFL, ramped from 1 to 150 over 150 nonlinear iterations

# 2D NACA 0012 Airfoil

- **Solutions computed using TMR Family II structured grid series**
  - 2x113x33, 2x225x65, **2x449x129**, 2x897x257, 2x1793x513, **2x3585x1025**
  - grid points listed in spanwise, streamwise, and normal directions

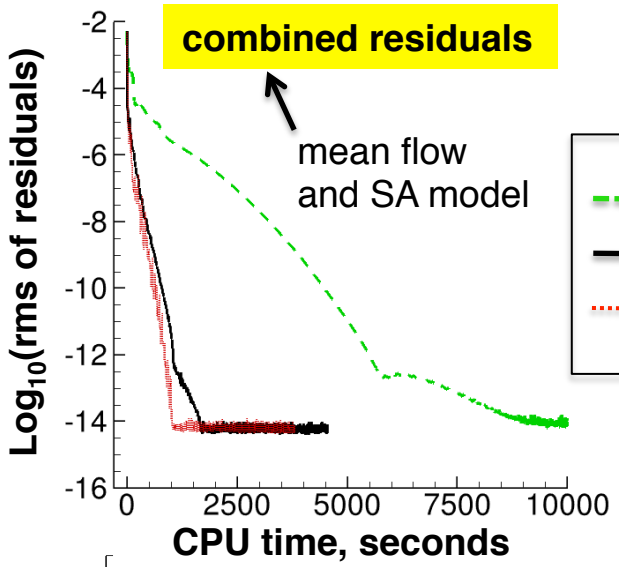


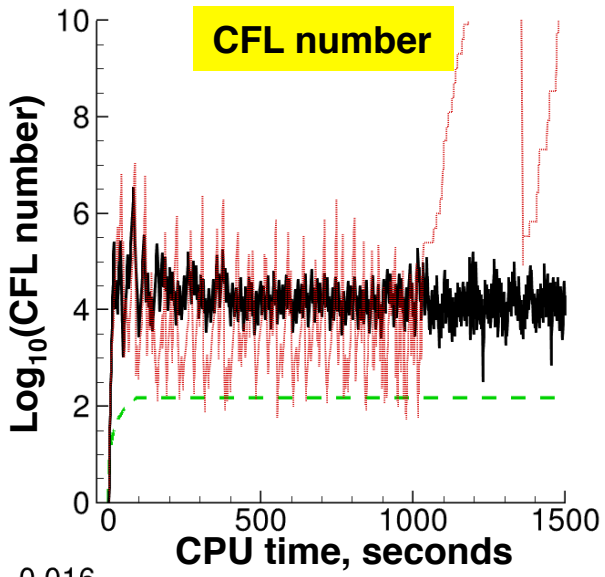

**Flow conditions: $M_\infty = 0.15$, $\alpha = 10°$, $Re_c = 6x10^6$**

**Solutions initialized using grid sequencing**

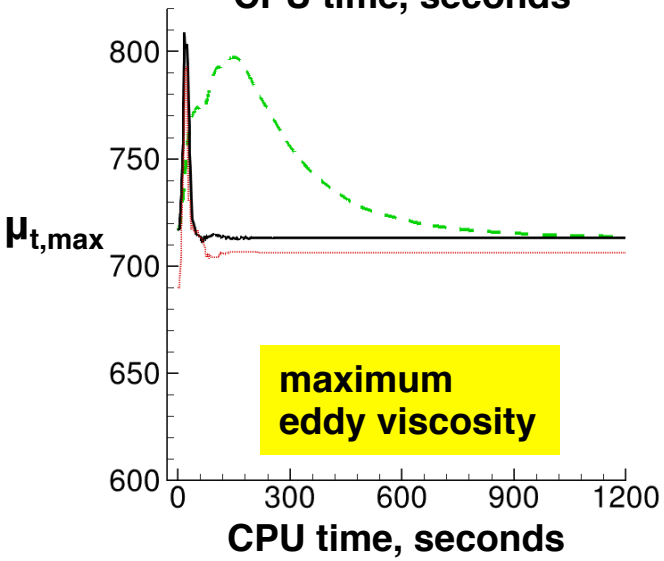
# 2D NACA 0012 Airfoil

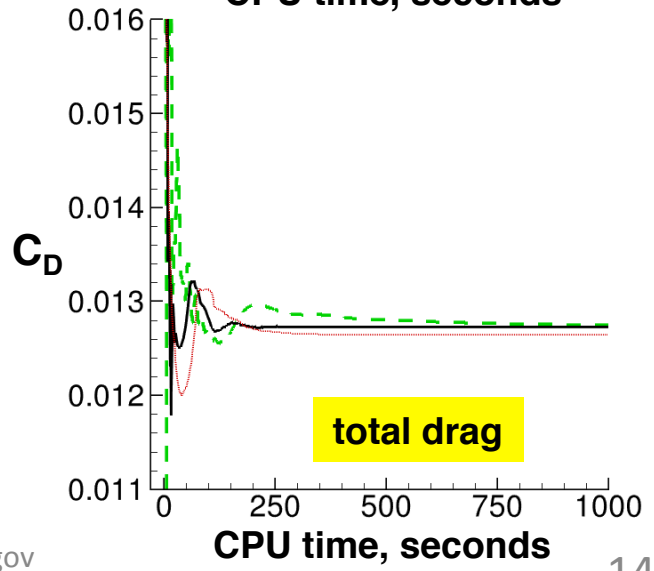
## Solution Convergence on 2x449x129 Grid




PA
PI-HANIM
LI-HANIM

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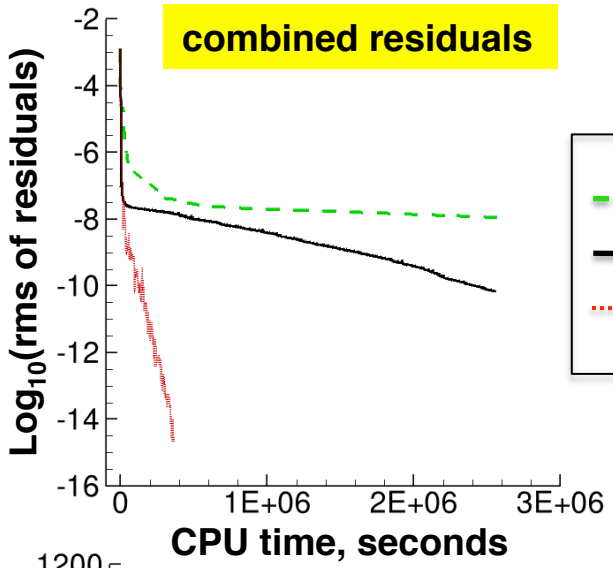
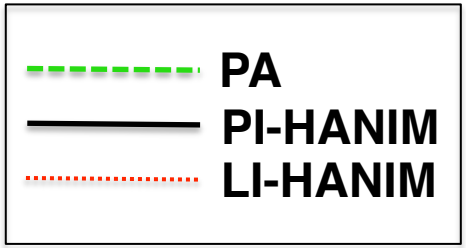
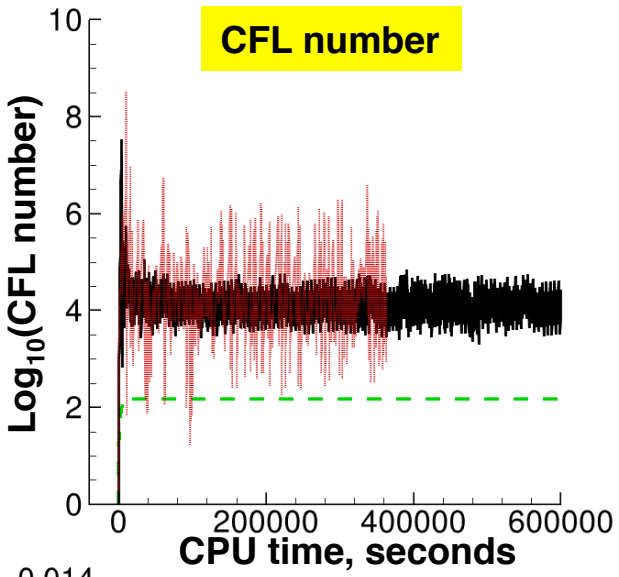
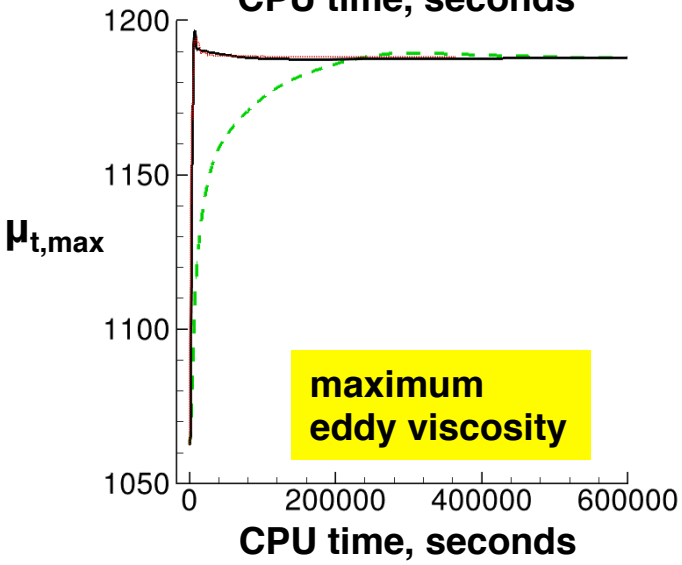
# 2D NACA 0012 Airfoil

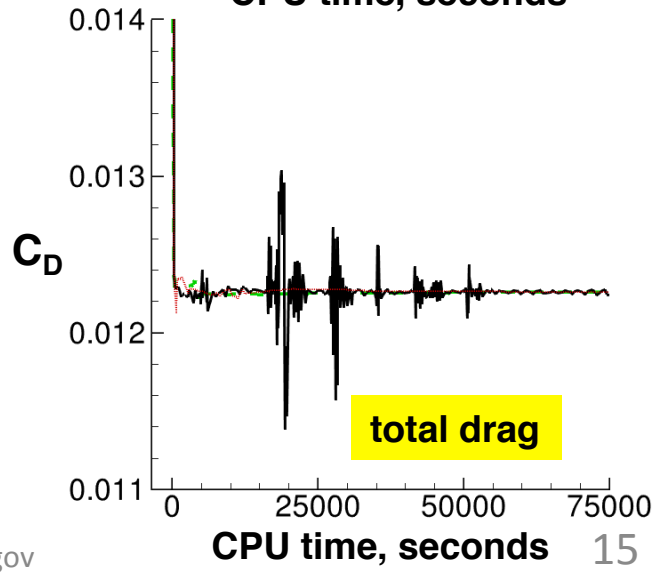
## Solution Convergence on 2x3585x1025 Grid

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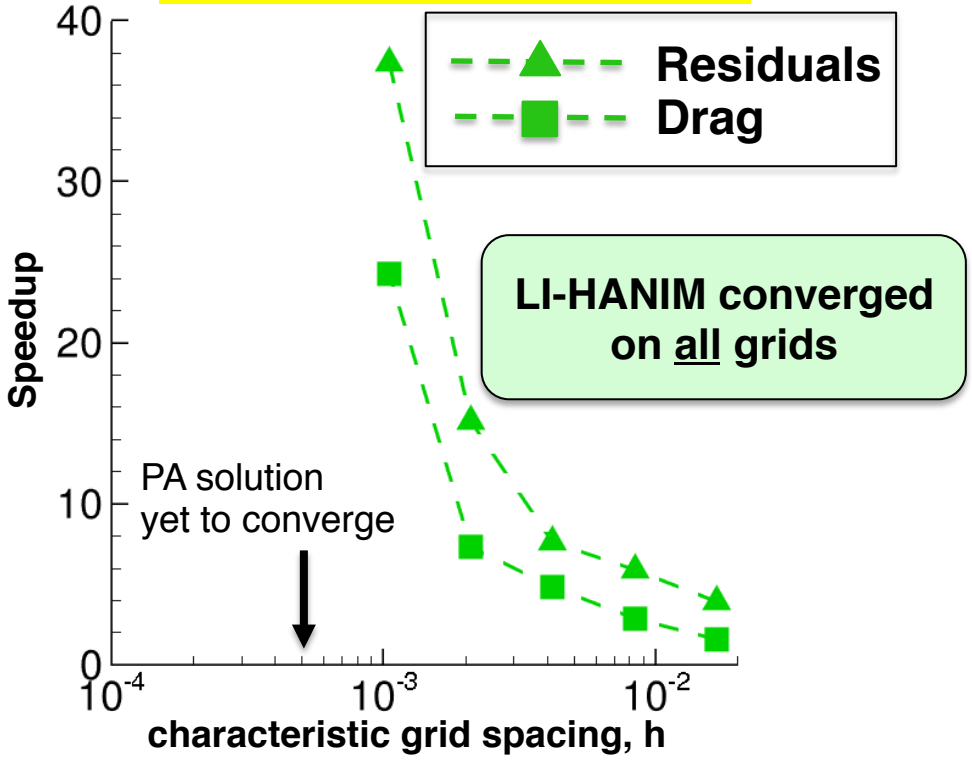
# 2D NACA 0012 Airfoil

## LI-HANIM Speedup for Converged* Solutions

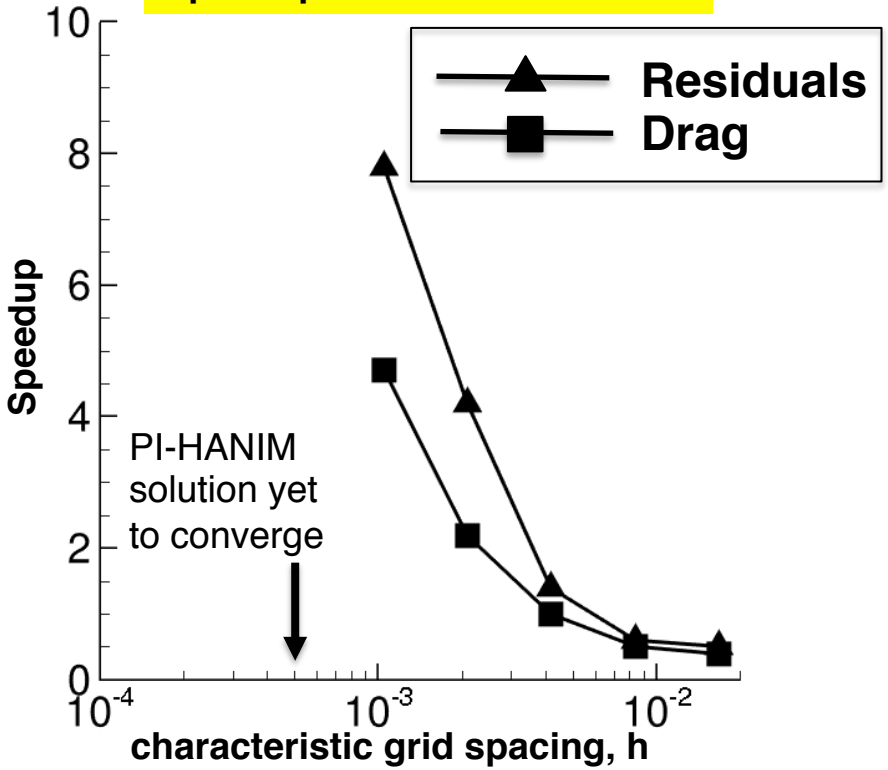
***combined residual rms $1.0 \times 10^{-13}$**
**force coefficients converge to six significant digits**

LI-HANIM speedup = method time to solution/LI-HANIM time to solution

**Speedup relative to PA method**

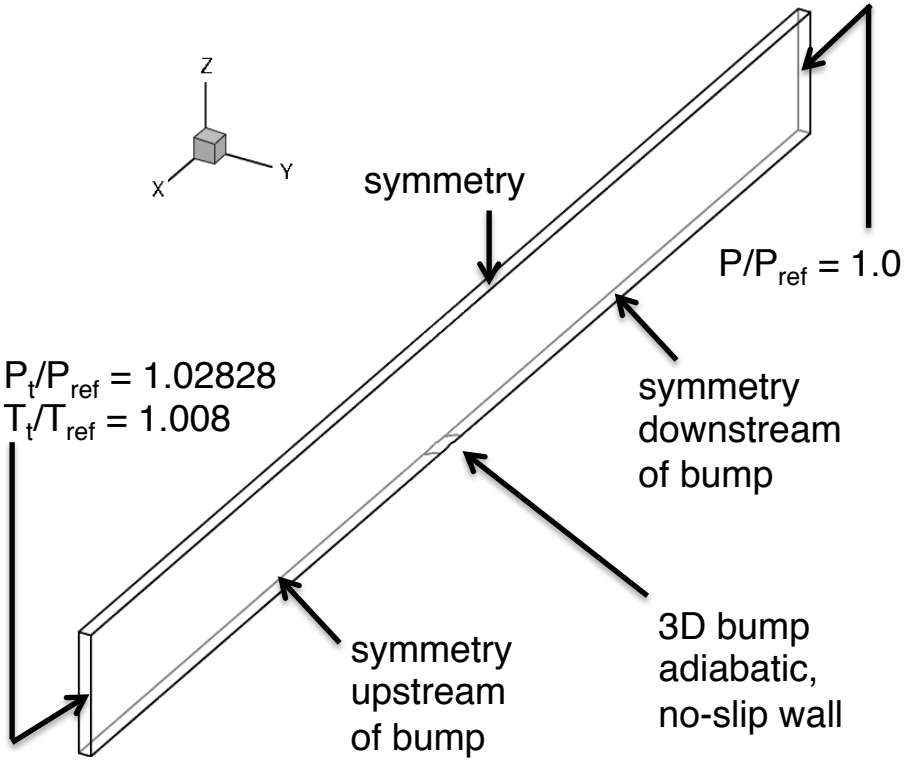


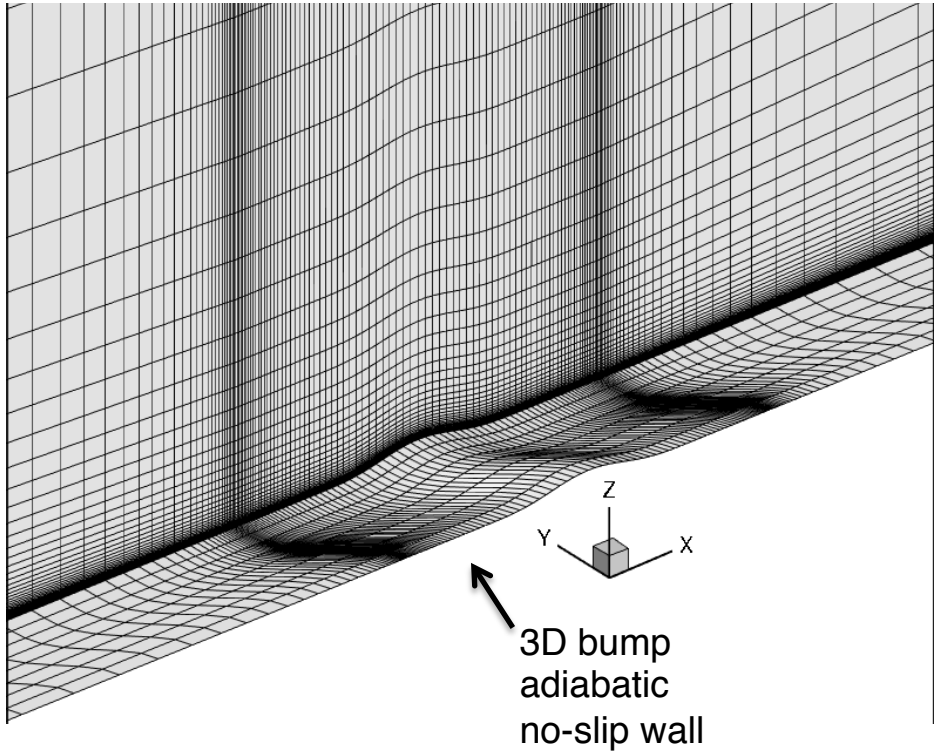

**Speedup relative to PI-HANIM**



# 3D Bump-in-Channel

- **Solutions computed using structured grid series**
  - 3x45x21, 5x89x41, 9x177x81, 17x353x161, **33x705x321**, 65x1409x641
  - grid points listed in spanwise, streamwise, and normal directions



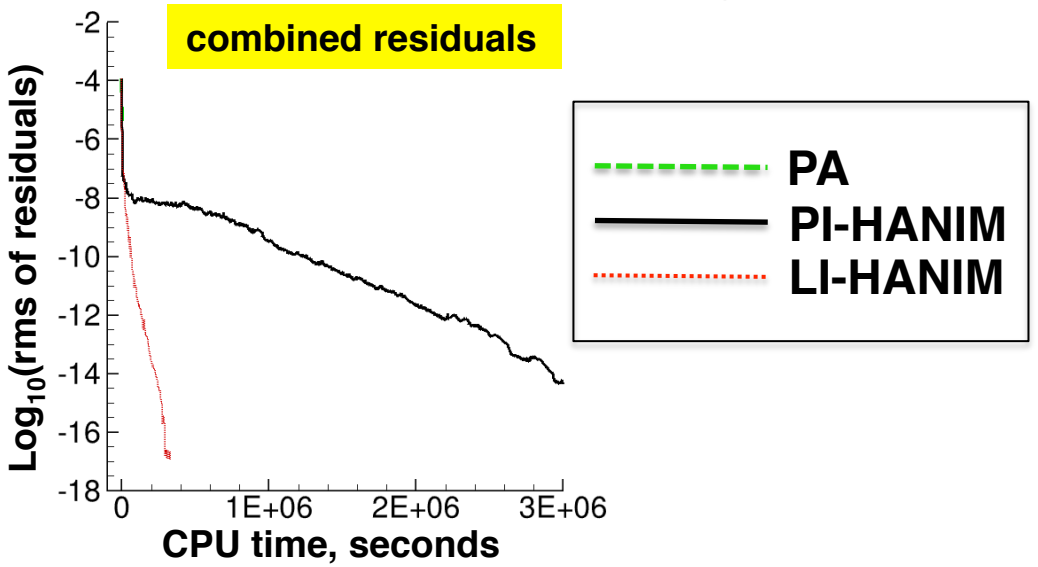



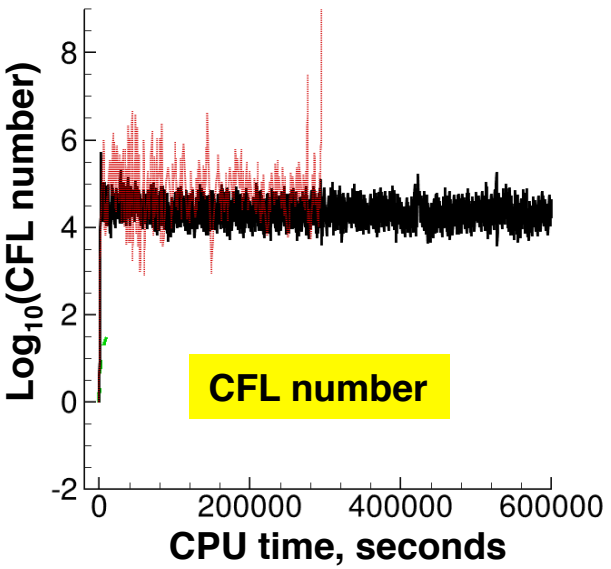

**Flow conditions: $M_\infty = 0.2$, $\alpha = 0°$, $Re_L = 3x10^6$**

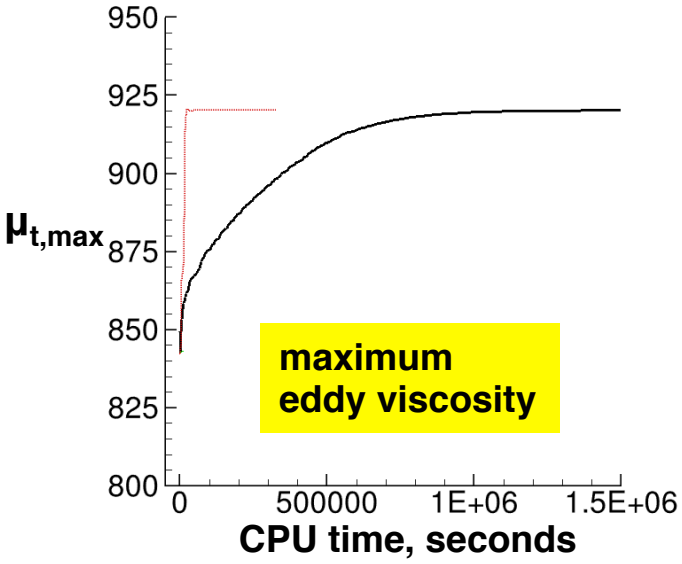
**Solutions initialized using grid sequencing**

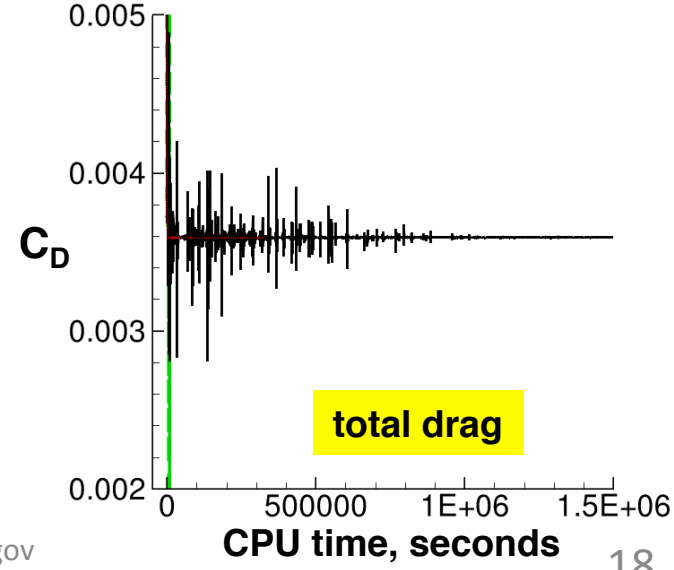
# 3D Bump-in-Channel

## Solution Convergence on 33x705x321 Grid

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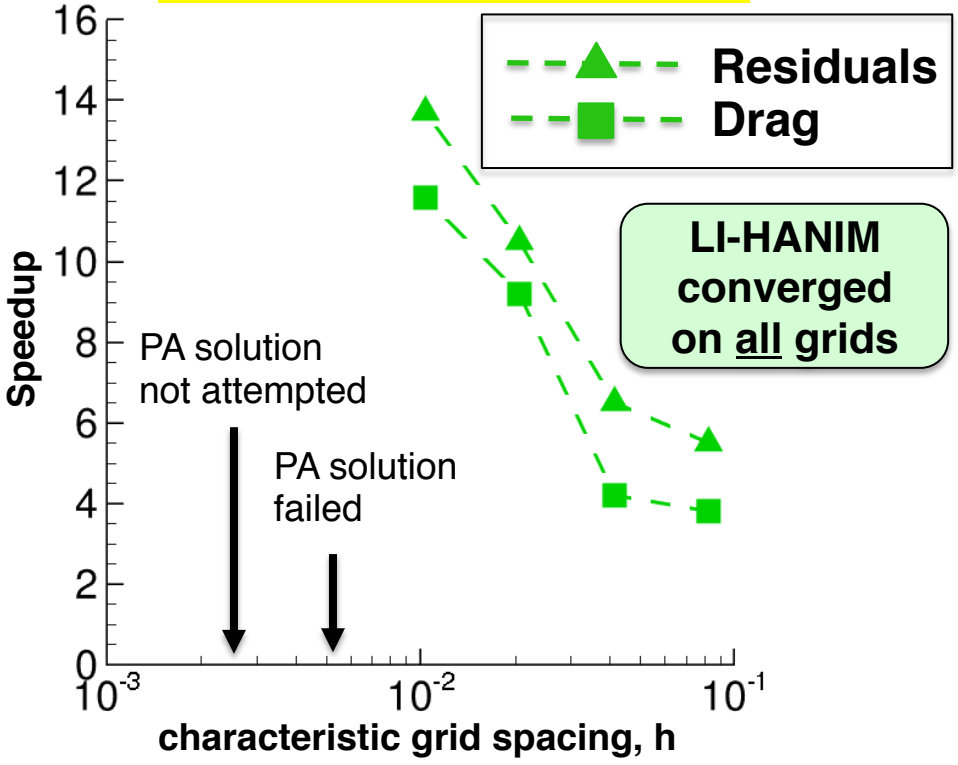
# 3D Bump-in-Channel

## LI-HANIM Speedup for Converged* Solutions

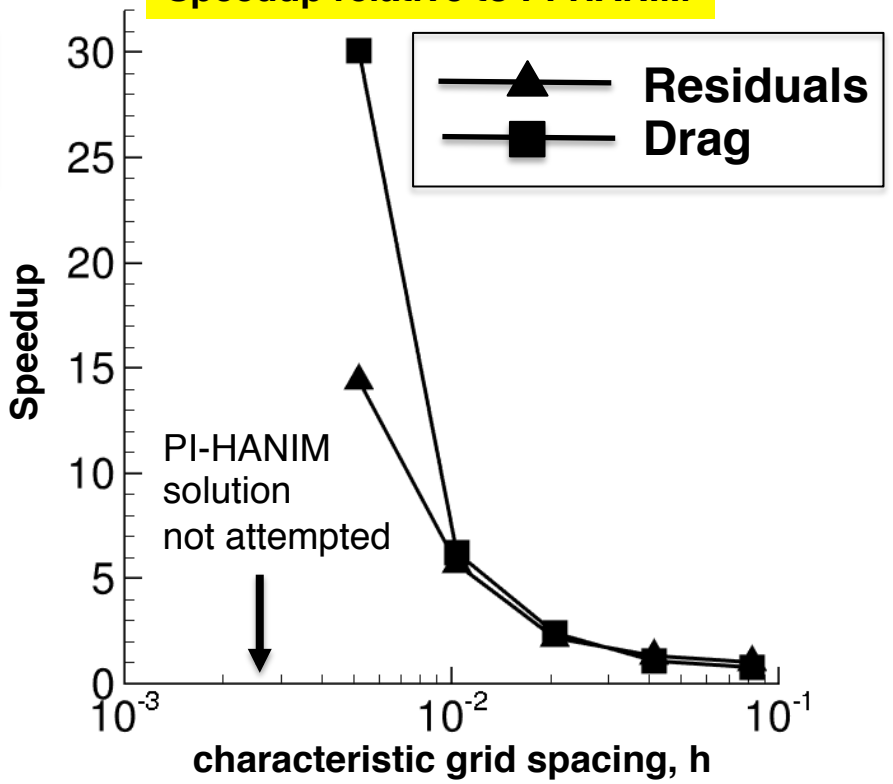
***combined residual rms $1.0 \times 10^{-13}$**
**force coefficients converge to six significant digits**

LI-HANIM speedup = method's time to solution/LI-HANIM time to solution

**Speedup relative to PA method**

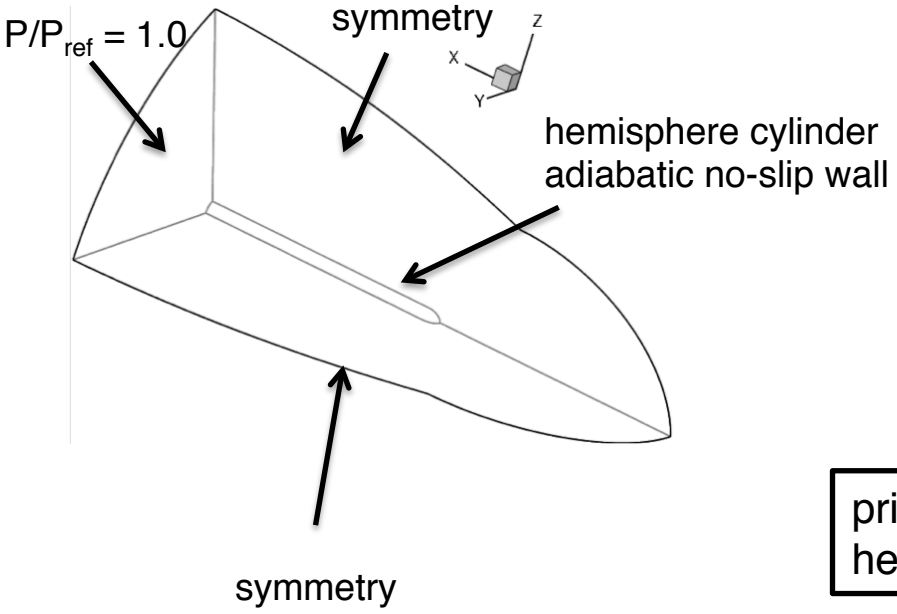


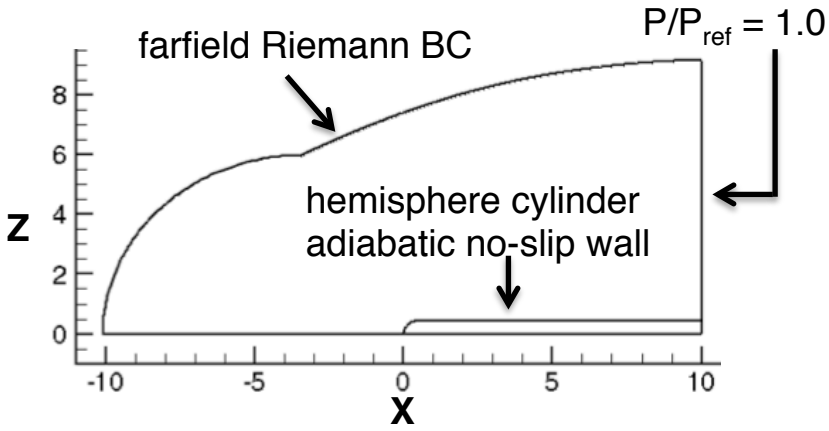

**Speedup relative to PI-HANIM**

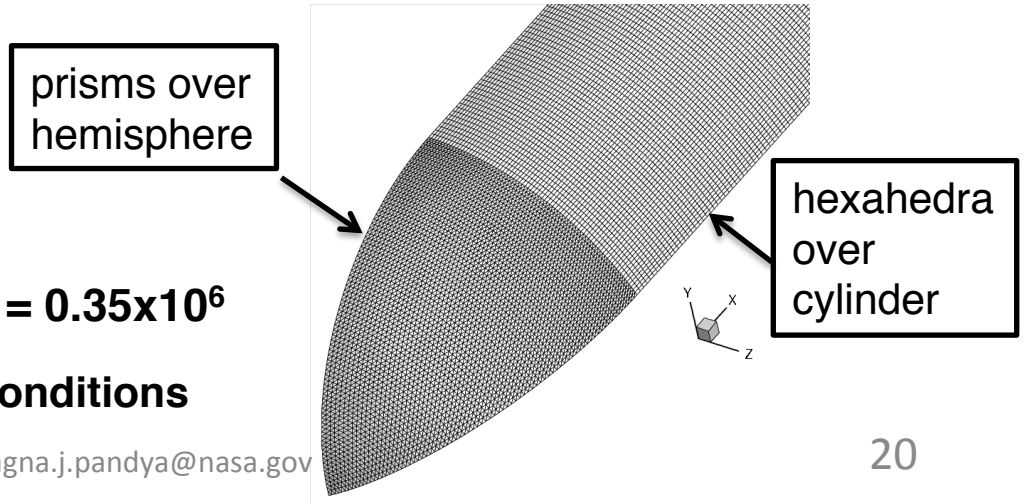


# 3D Hemisphere-Cylinder

- **Solutions computed using mixed-element unstructured grid series**
  - 355,200 cells in coarse grid, 2,841,600 cells in medium grid, and 22,732,800 cells in fine grid
  - 60° circumferential domain




**Flow conditions: $M_\infty = 0.6$, $\alpha = 0°$, $Re_L = 0.35 \times 10^6$**

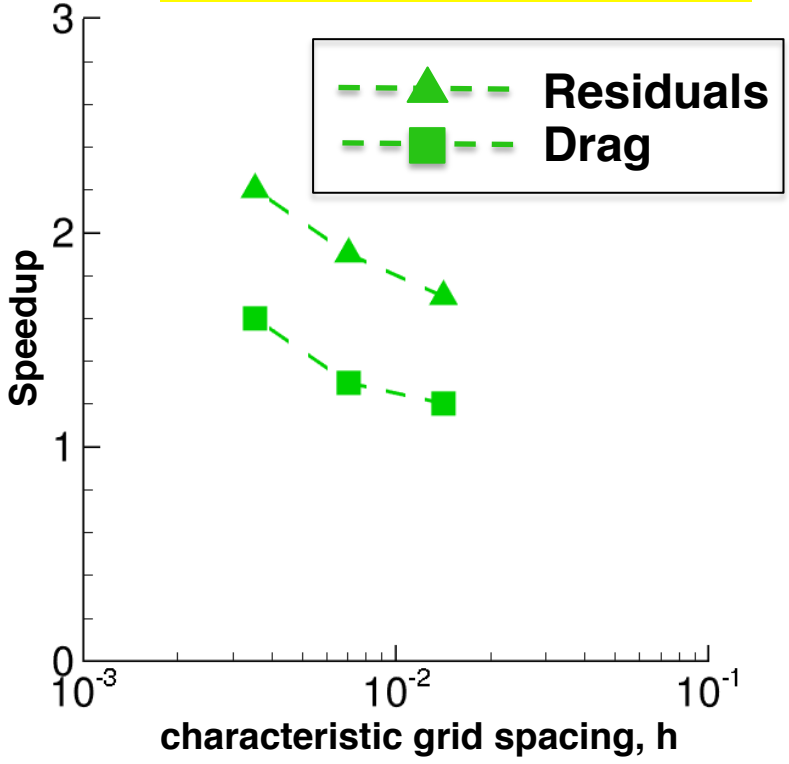
**Solutions initialized using freestream conditions**

# 3D Hemisphere-Cylinder
## LI-HANIM Speedup for Converged* Solutions

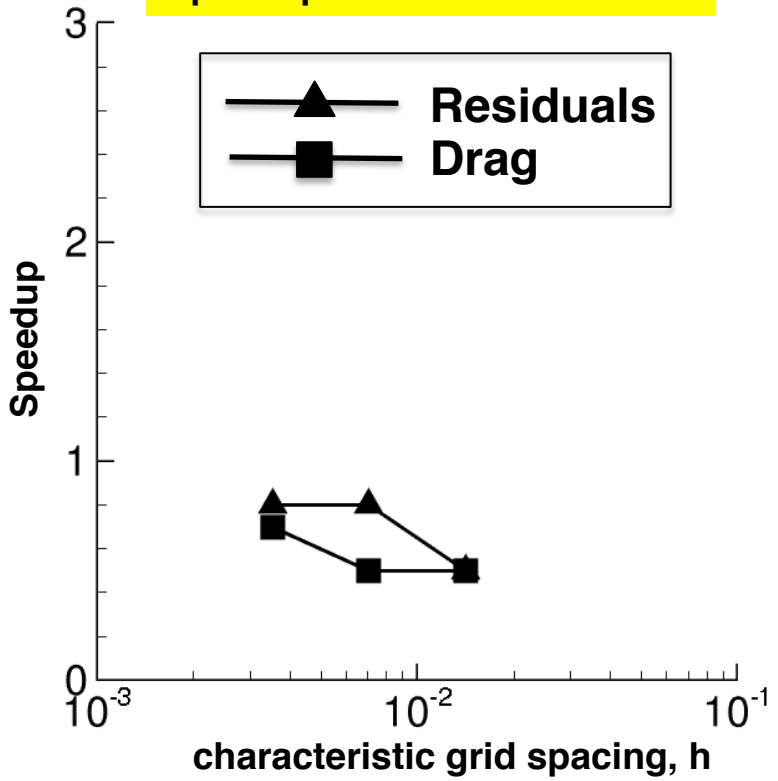
***combined residual rms $1.0 \times 10^{-13}$**
**force coefficients converge to six significant digits**

LI-HANIM speedup = method's time to solution/LI-HANIM time to solution

**Speedup relative to PA method**



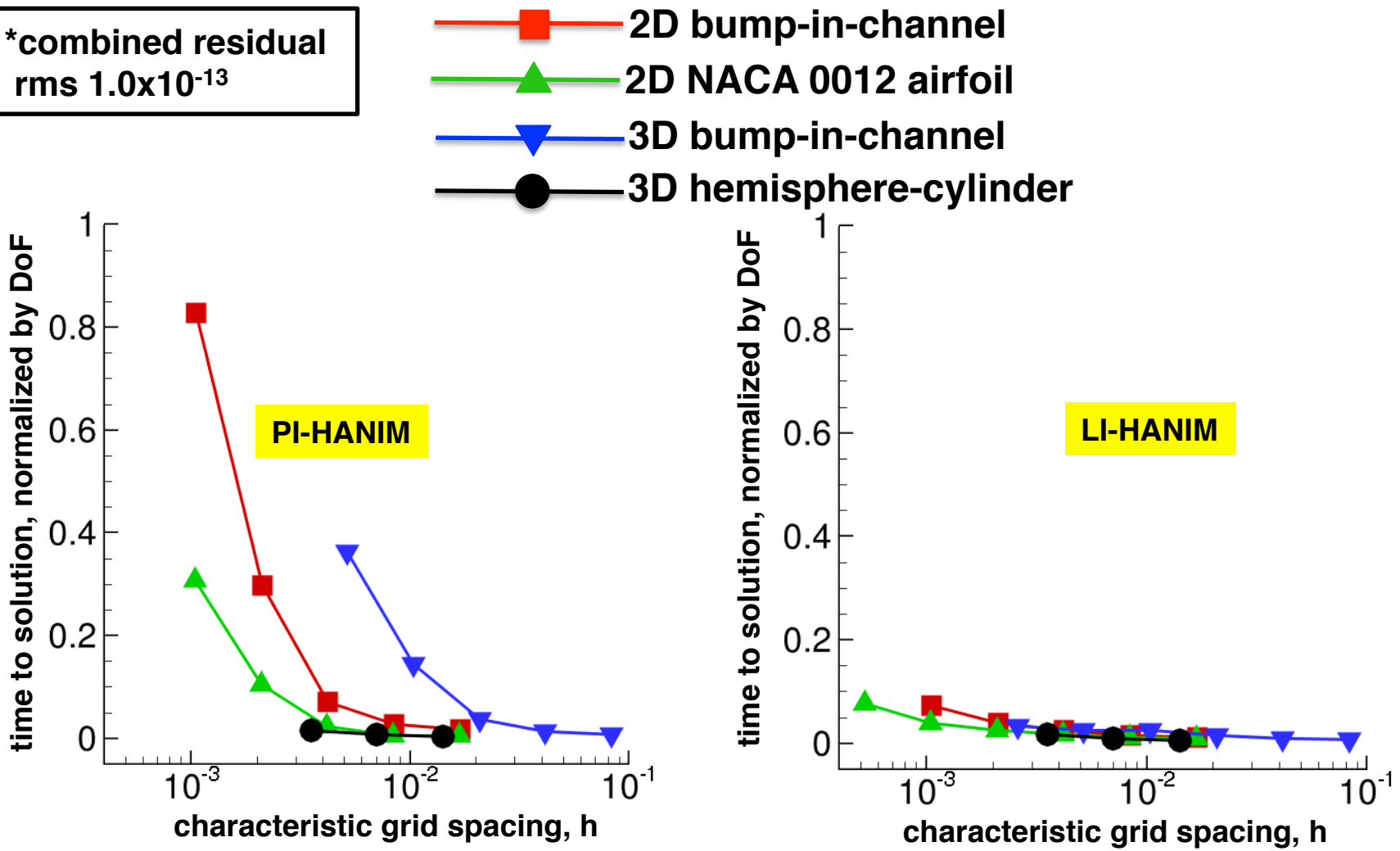

**Speedup relative to PI-HANIM**



# HANIM Convergence

## Time to Target Level* Residuals for Four Cases

*combined residual rms $1.0 \times 10^{-13}$



# Concluding Remarks

- **Enhancements for mixed-element USM3D to further improve efficiency and accuracy of CFD solutions**
  - multicolor line-implicit preconditioner
  - discretely-consistent and general symmetry boundary condition
  - improved discretization of turbulence model source term using line-mapping method
- **Iterative convergence of line-implicit HANIM assessed relative to point-implicit HANIM and PA method on four turbulent flow cases**
  - 2D bump in a channel, 2D NACA 0012 airfoil, 3D bump in a channel, 3D hemisphere cylinder
- **Only line-implicit HANIM met convergence targets for all cases**
  - rms norm of combined mean flow and turbulence model residuals $\leq 10^{-13}$
  - aerodynamic coefficients converged to six significant digits

# Concluding Remarks

- **Line-implicit HANIM relative to point-implicit HANIM**
  - at least factor 2.1 speedup for bump cases and NACA 0012 airfoil on finer grids, speedup higher than 10 on many grids
  - negligible speedup or even minor slowdown on coarse grids
  - slowdown for 3D hemisphere cylinder case, more competitive in grid refinement
  - less case-to-case variations in performance
  - less degradation in performance with grid refinement
- **Line-implicit HANIM relative to PA method**
  - more efficient across all cases
  - at least factor 6.2 speedup for bump cases and NACA 0012 airfoil on finer grids, speedup higher than 10 on many grids
- **Discretely-consistent and general symmetry boundary condition enabled efficient simulation of 3D hemisphere cylinder case**
  - one sixth of the grid for the full computational domain

# Future Directions

- **Parallelize current improvements**
- **Develop line generation algorithm for general unstructured grids**
- **Assess line-implicit HANIM on more 3D cases**
  - transonic/supersonic flows
  - tetrahedral grids
- **Seek grid-independent convergence rate**
  - agglomeration scheme for grid sequencing and multigrid
  - linear multigrid for preconditioner
  - nonlinear multigrid solver

# Acknowledgments


- **Present study funded by the NASA Aeronautics Research Mission Directorate**
  - Transformative Aeronautics Concepts Program, Transformative Tools and Technologies project
  - Airspace Operations and Safety Program, Airspace Technology Demonstrations project
- **Drs. H. Nishikawa (NIA) and E. Parlette (ViGYAN, Inc.) provided utilities to generate grids for 3D hemisphere-cylinder case**